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DESCRIPTION OF THE WARM CORE TURBINE FACILITY AND THE WARM ANNULAR CASCADE FACILITY RECENTLY INSTALLED AT NASA LEWIS RESEARCH CENTER

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ABSTRACT

The two new facilities have been installed and operated at their design or rated conditions. The important feature of both of these facilities is that the ratio of turbine inlet temperature to coolant temperature encountered in high temperature engines can be duplicated at moderate turbine inlet temperature. Included in the discussion are the limits of the facilities with regard to maximum temperature, maximum pressure, maximum mass flow rate, turbine size, and dynamometer torque-speed characteristics.

AIRCRAFT ENGINES for both commercial and military applications are characterized by compressor drive turbines that operate at increasingly higher temperatures. The required turbine coolant results in aerodynamic losses that significantly penalize the engine performance. Many studies have been and are being made to determine the extent of these losses, minimize their effect, and properly account for them analytically in the turbine design programs employed by the designer. Much of this work done in-house at Lewis Research Center and funded by NASA at engine contractors' facilities is summarized in reference (1).* The bulk of this work was done at turbine primary air-to-coolant inlet temperature ratios of 1. This permitted a fast and low cost method of determining the major parameters influencing turbine performance. However, a number of actual engine flow property ratios could not be simultaneously set at the cold conditions.

Consequently, two warm facilities were recently designed and installed at Lewis Research Center to operate at an inlet gas temperature of 1410°R (783°K) to test full annular cascades and rotating turbine stages. This allows an actual primary air-to-coolant-temperature ratio to be set which duplicates that encountered in high temperature engines. This paper describes the major components of these facilities, the operating limitations, and the operating experience to date.

DESCRIPTION OF WARM ANNULAR CASCADE

The warm annular cascade is shown in (Fig. 1a). Air from the laboratory 40 psig combustion air system is supplied through a 12" pipe. Air flow is metered with a venturi meter of 5.8 inch (14.73 cm) throat diameter, which is also common to the warm core turbine facility. The cascade inlet total pressure is controlled by a 10" butterfly valve. The air then passes through a conical transition section to the combustors which consist of three J-47 cans where natural gas is burned to achieve the desired cascade inlet temperature, 250°-1000°F (121°-538°C). Cascade inlet temperature is maintained with an automatic controller. The cascade inlet transition

*Numbers in parentheses designate References at end of paper.

section is about four feet long with a 24" diameter and contains a perforated plate mixer at about 1/3 of its length.

The test section contains the inner and outer bellmouth fairings and centerbody. The initial core vane test configuration has a 20 inch (.51 m) tip diameter with a 1.5 inch (3.8 cm) blade span and consists of 36 stator vanes. Five of these are test vanes and can be removed from the outside such that various cooling methods can be tested without disassembling the test section. The hub walls and tip walls of the five vane sector are film cooled. Four independently controlled cooling circuits are provided for the: (1) test vanes, (2) test vane inner wall, (3) test vane outer wall, and (4) remaining 31 vanes. The cooling air is supplied from the laboratory 125 psig comustion air system. Each cooling circuit has a pressure control valve and a calibrated ASME flat plate orifice flow meter.

After leaving the test section the flow is directed through a flow straightener to remove the stator exit swirl. A water spray is then used to reduce the gas temperature to less than 200^{o}F. The flow is then directed through the exhaust control valve to the laboratory altitude exhaust system.

At the inlet and exit stations (Fig. 2) the instrumentation consists of temperature and pressure probes and rakes as well as wall static taps. At the stator exit (Station 2) static pressure is measured by 21 hub wall static taps and 21 tip wall static taps arrayed across the center passage of the five test vane sector.

The principal measurements are circumferential surveys of stator exit total pressure and temperature. These surveys are done at several radial positions using the probe shown in (Fig. 3). These data are used to calculate mass flow, energy, axial and tangential momentum. These quantities are integrated circumferentially and radially. The continuity and momentum equations are then used to calculate after-mixed values of flow, pressure, and velocity.

DESCRIPTION OF WARM CORE TURBINE FACILITY

The warm turbine facility is also shown in (Fig. 1a). Air is supplied from the laboratory 40 psig combustion air system through

a 12" pipe. The inlet control valves consist of a 10" manually operated butterfly valve and a 6" automatically controlled by-pass valve. The natural gas fueled combustor is identical to that of the annular cascade facility. The inlet transition section consists of a conical segment followed by a cylindrical segment, the diameter varying from 24 to 30 inches (61 to 76 cm) from inlet to outlet. This transition piece contains a perforated plate flow mixer at the start of the cylindrical segment.

The turbine test section contains the fairings and centerbody to match the turbine dimensions. The initial turbine has a tip diameter of 20 inches (50.8 cm) and a blade span of 1.5 inches (3.8 cm) (Fig. 4).

Downstream of the turbine the air is cooled to 200°F (93°C) or lower by water sprays. A photograph of the rotor installed in the facility is shown in (Fig. 5) where the spray bars can be seen.

The inlet static pressure is measured with 10 (five inner, five outer) wall static taps in the annulus upstream of the stator blades (Station 1) (Fig. 4). Inlet total temperature is measured with 25 shielded thermocouples located with five each on five inlet frame struts. The outlet static pressure (Station 2) is measured with 12 wall static taps (six inner, six outer). The flow angle is also measured at Station 2 with self-aligning probes at four circumferential positions. A photograph of the combination angle-pressure-temperature probe is shown in (Fig. 6). The inlet and outlet total pressure was then calculated using these measurements.

The turbine shaft output power is absorbed with a direct-drive eddy current dynamometer which also controls turbine speed. The dynamometer is rated at 3000 HP at 5000 to 25000 RPM and is water cooled with a recirculatory cooling system and heat exchanger. The primary torque measurement is made with a brushless rotating torque meter (Fig. 7) mounted between the turbine and the dynamometer. Static torque is also measured on the dynamometer stator, which is cradled on hydrostatic trunion bearings. Rotor tip clearance is measured with a self-calibrating touch probe shown in (Fig. 8).

In addition to the primary air flow, the turbine facility is provided with auxilliary air circuits supplied from the laboratory 125 psig system as shown in Table 1. For the initial testing solid blading and solid stator shroud rings were used and only the thrust balance and rotor disc coolant circuits were activated.

The auxilliary air circuits are each equipped with an inlet control valve and calibrated orifice run containing an ASME flat plat orifice.

Turbine efficiency is based on actual specific work output calculated from measured values of torque output, speed, and weight flow. Ideal specific work output is calculated from measured values of turbine inlet total temperature and calculated values of inlet and exit total pressures. The pressures are calculated from measured values of inlet total temperature and local values of static pressure, flow angle, mass flow rate, and annular area. Exit total temperature is calculated from inlet total temperature and actual specific work output. Corrections are also made for calibrated turbine bearing losses and power absorbed by the rotor disc cooling air.

LIMITING OPERATING CONDITIONS - The limiting operating conditions of both facilities are summarized in Table 2. The temperature and pressure of 1410^{o}R (783^{o}K), 45 psia (3.1 * 10^5 pascals) respectively, were used as maximum values in the facility design. The mass flow of 27 lb/sec (12.2 Kg/sec) is a limit of the laboratory 45 psig air system and the piping flow losses. The maximum ratio of turbine inlet temperature to coolant temperature is 2.65, and any lower ratio could be obtained by reducing turbine inlet temperature.

OPERATING EXPERIENCE - The warm cascade facility has been operated for an accumulated time of 90 hours. Over 200 data points have been taken. (Fig. 9) is a typical plot of the variation in inlet total temperature taken during a test run. Substantial gradients exist both radially and circumferentially. There is about an 80^{o}F (44^{o}C) difference between the maximum and minimum temperatures measured. This problem resulted from the short mixing length available in the test cell between the combustors and th test cascade (Fig. 1). Turning vanes are being

installed at the outlet of each combustor can to add swirl and increase mixing before the perforated plate. This was done to the companion turbine facility which had the same space limitations and proved to be very effective. A contour plot of total pressure ratio taken at the cascade exit survey plane is shown in (Fig. 10). Good definition of wake and core loss patterns are seen to exist.

The warm core turbine has been operated for an accumulated time of 200 hours. A total of 1000 data points have been taken. The variation in turbine inlet temperature measured at an average temperature of 1400°R is shown in (Fig. 11). Considering the limited mixing length available, this distribution is considered to be very good. The maximum deviation from the average is less than 0.7 percent.

The radial variation in turbine exit flow angle as measured by the self-aligning probes is shown in (Fig. 12) for the condition of design speed and turbine work output. Also shown on the figure is the design variation from hub to tip. The probe data indicate good agreement with the design variation with about three degrees of overturning at the 88 percent radial location.

Rotor tip clearance losses are very significant for present and future core turbines. Good definition of actual running clearance is therefore important to properly interpret component test results. (Fig. 13) shows the variation in high-blade tip clearance as a function of speed and temperature for this turbine. The data was taken by the self-calibrating touch probe of (Fig. 8) and the results indicate it to be a very useful tool for turbine testing. A total of three of these probes are being installed in the next test turbine to measure roundness and also to calibrate a laser probe installed to measure individual blade clearance.

As mentioned before, the primary test measurements are inlet temperature, static pressures, rotative speed, torque output, mass flow rate, and exit flow angle. The dynamometer controlled speed to within 2 RPM at 10,000 RPM operating conditions. Static pressure measurements were no problem and inlet temperature variations have been shown. (Figs. 14, 15, and 16) show typical variations in torque, flow, and exit angle as a function of turbine pressure ratio at design

speed. All three variations are smooth and consistent, which would tend to indicate good quality performance data are being obtained in this facility.

CONCLUDING REMARKS

Two warm core turbine test facilities recently installed at the Lewis Research Center are described in this paper and typical data are presented The facilities allow testing at the actual engine temperature ratio (between the hot gas primary flow and the turbine coolant) at moderate test temperatures. Although no mention was made of controls, both facilities were designed with data acquisition and control features to minimize test time.

The facilities are considered a major asset to required testing necessary to advance core turbine technology for future gas turbine engines.

REFERENCES

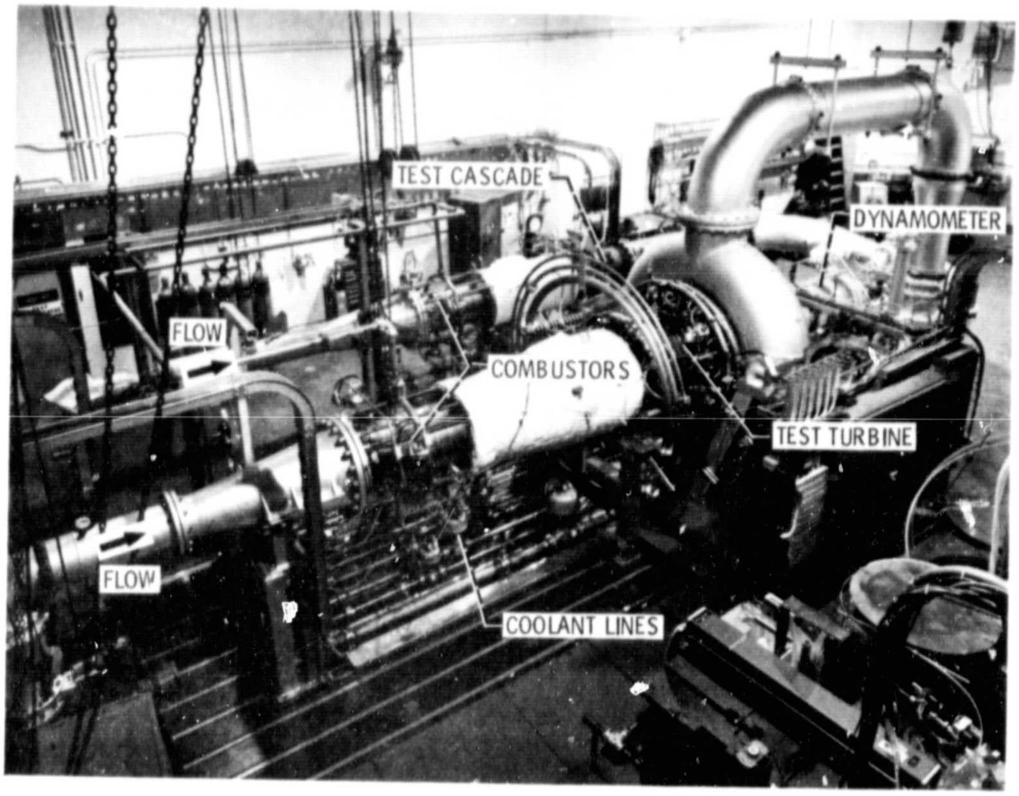
1. T. P. Moffitt, F. S. Stepka, and H. E. Rohlik, "Summary of NASA Aerodynamic and Heat Transfer Studies in Turbine Blades and Vanes." NASA TM X-73518, 1976.

Table 1 - Turbine Coolant Circuits

Cooling Circuit Function	Maximum Flow lb/sec	(kg/sec)
Stator outer wall	0.5	(.23)
Stator inner wall	0.3	(.14)
Stator blade	1.0	(.45)
Rotor blade	1.9	(.86)
Rotor disc	0.3	(.14)
Thrust balance	1.0	(.45)

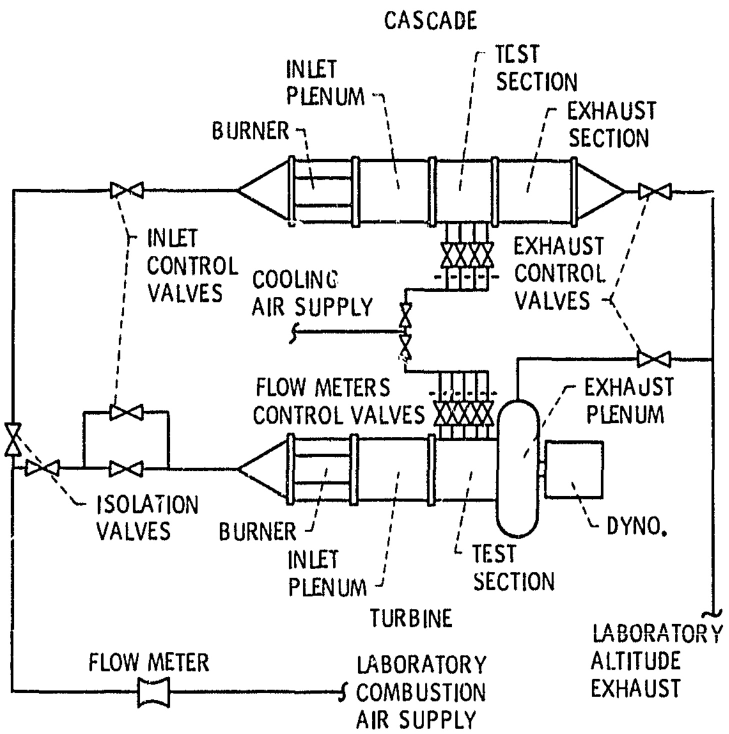
Table 2 - Facility Capabilities

	Facility	
	Turbine	Cascade
Max. temperature, ^{o}R (K)	1410 (783)	1410 (783)
Max. pressure, psia (Pascals)	45 ($3.1 * 10^5$)	45 ($3.1 * 10^5$)
Max. flow, lb/sec (kg/sec)	27 (12.2)	27 (12.2)
Max. speed, RPM	25,000	-----
Max. power, HP (KW)	3,000 (2.24)	-----



(a) PHOTOGRAPH.

Figure 1. - Warm core turbine facilities.



(b) SCHEMATIC.

Figure 1. - Concluded.

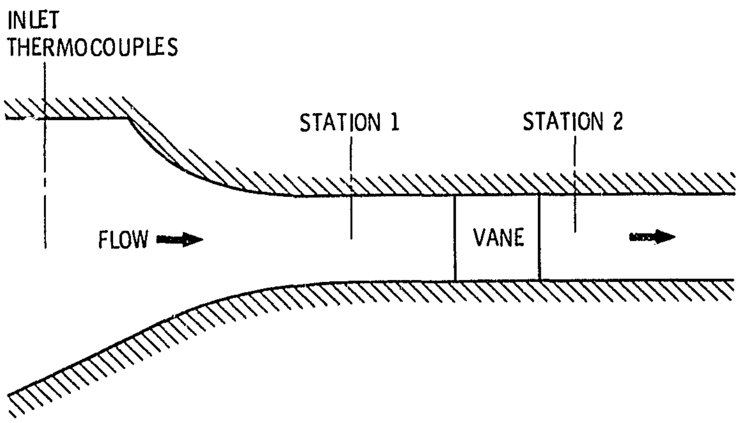


Figure 2. - Cascade flowpath and station locations.

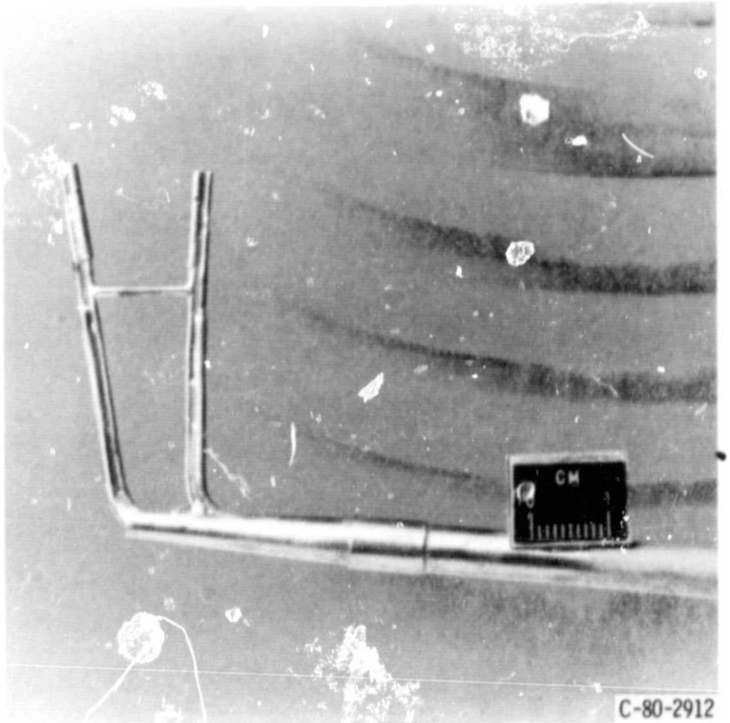


Figure 3. - Vane exit survey probe.

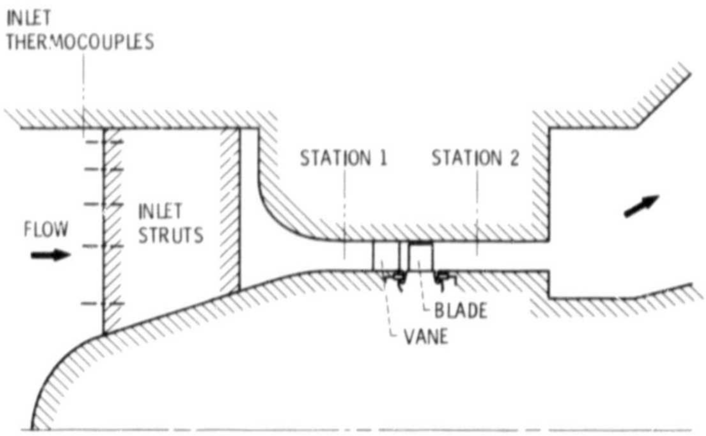


Figure 4. - Turbine flowpath and station locations.

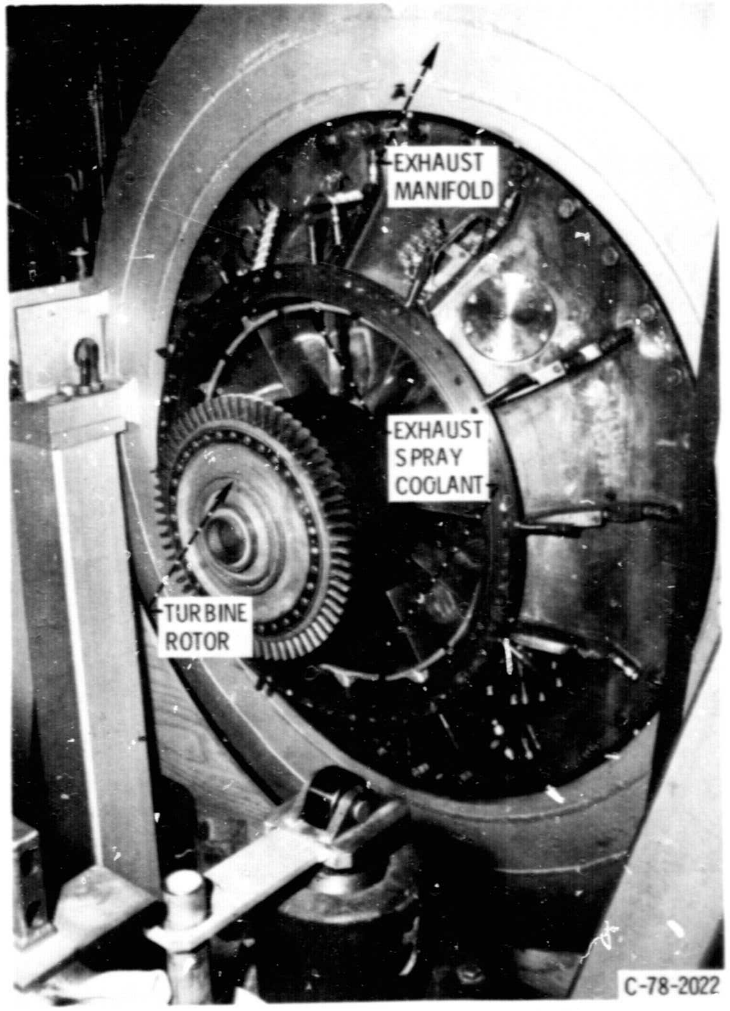


Figure 5. - Turbine rotor installed in test facility.

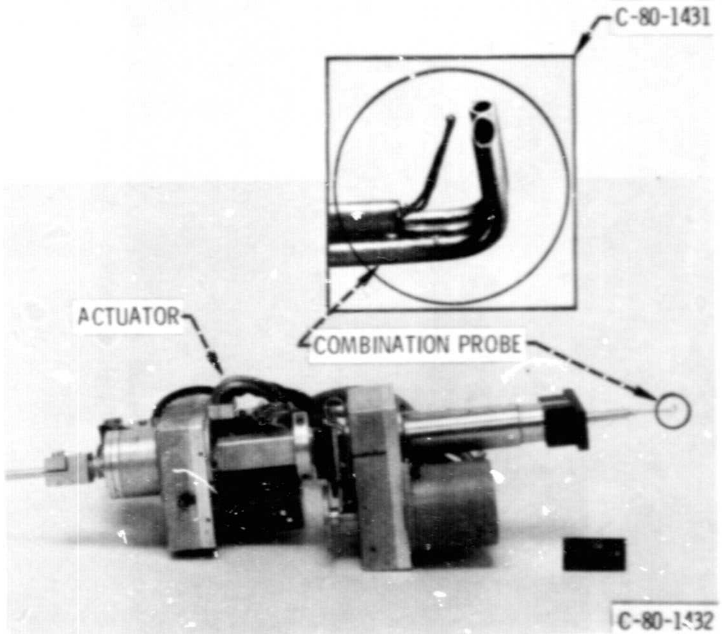


Figure 6. - Turbine exit survey probe.

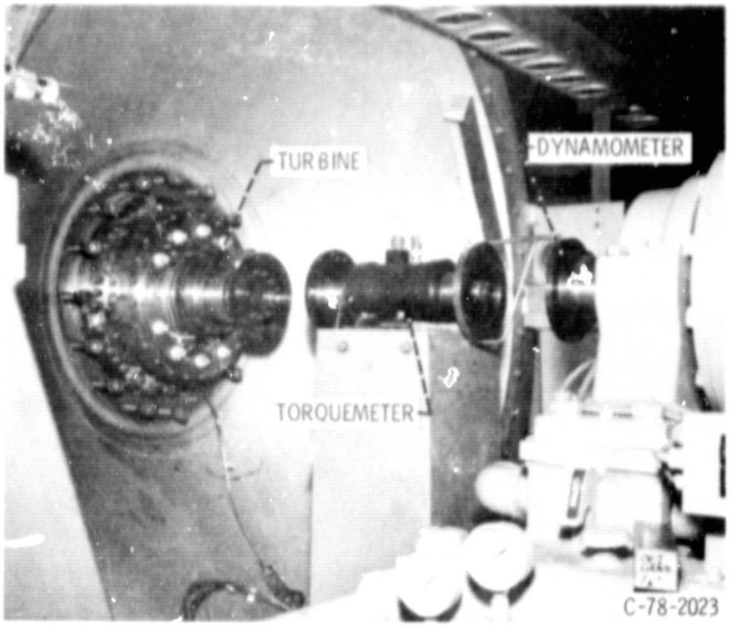


Figure 7. - Inline brushless torquemeter.

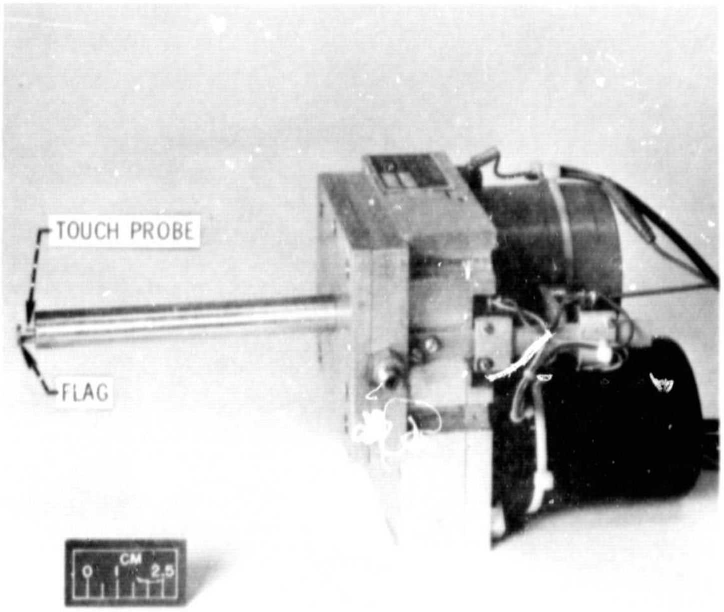


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Figure 8. - Blade tip clearance probe.

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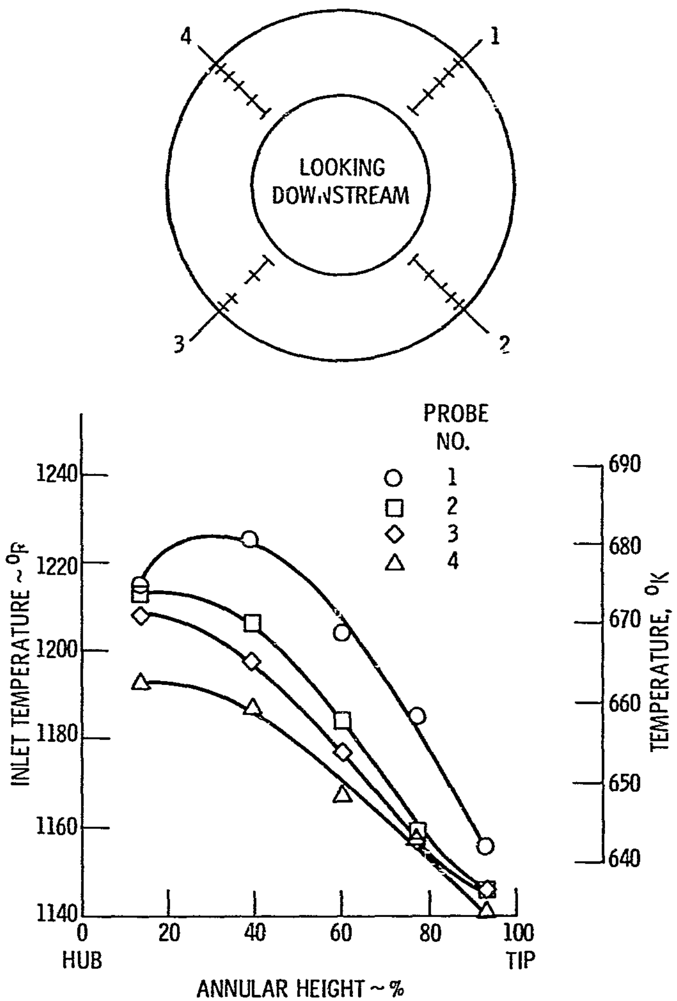

Figure 9. - Cascade inlet temperature distribution.

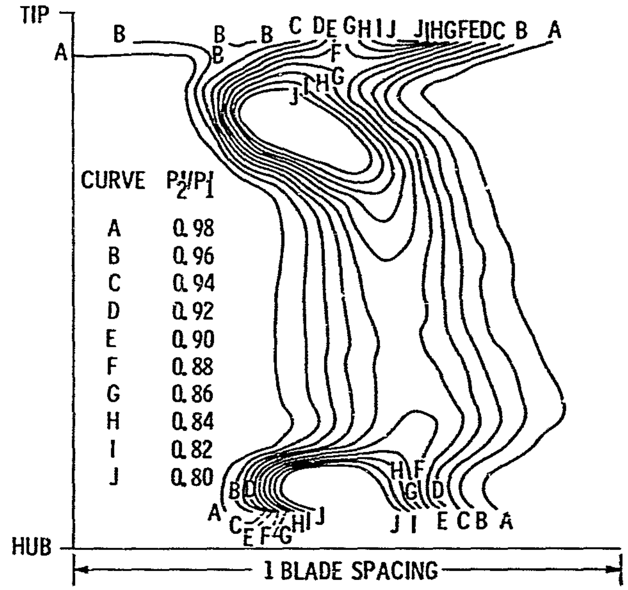

Figure 10. - Cascade exit survey.

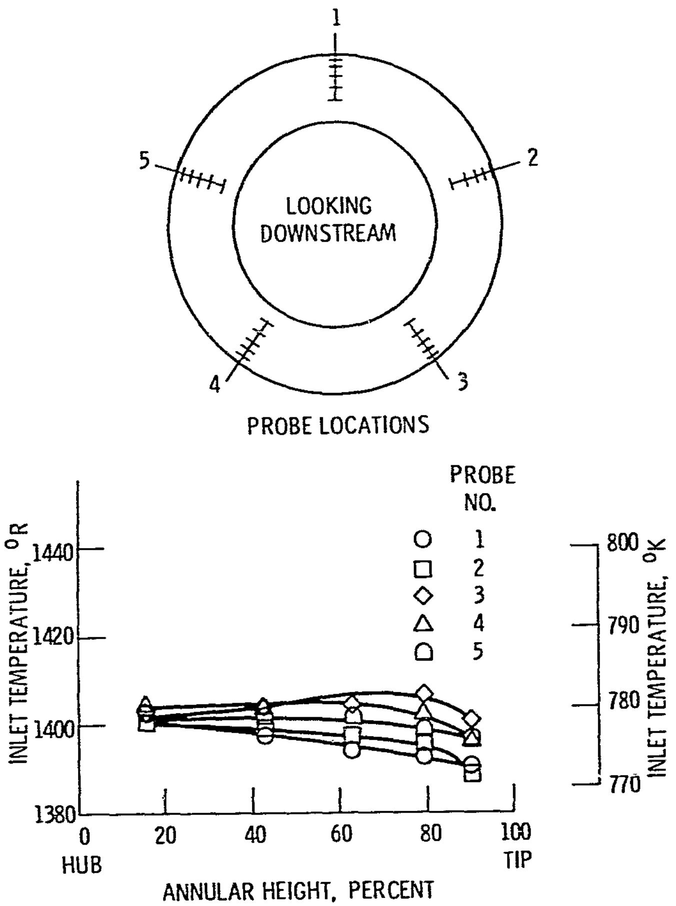

Figure 11. - Turbine inlet temperature distribution.

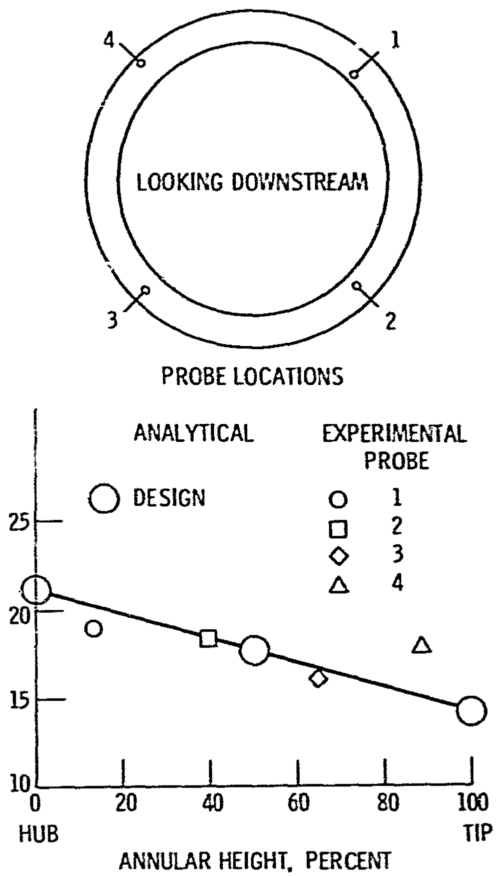

Figure 12. - Turbine exit flow angle radial gradient.

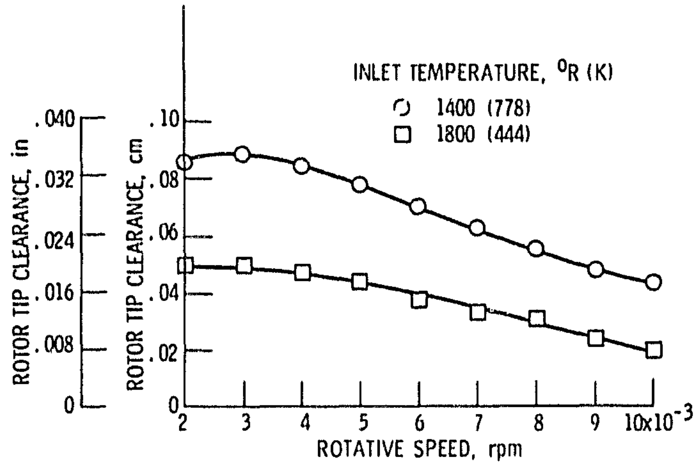

Figure 13. - Effect of speed and temperature on rotor tip clearance.

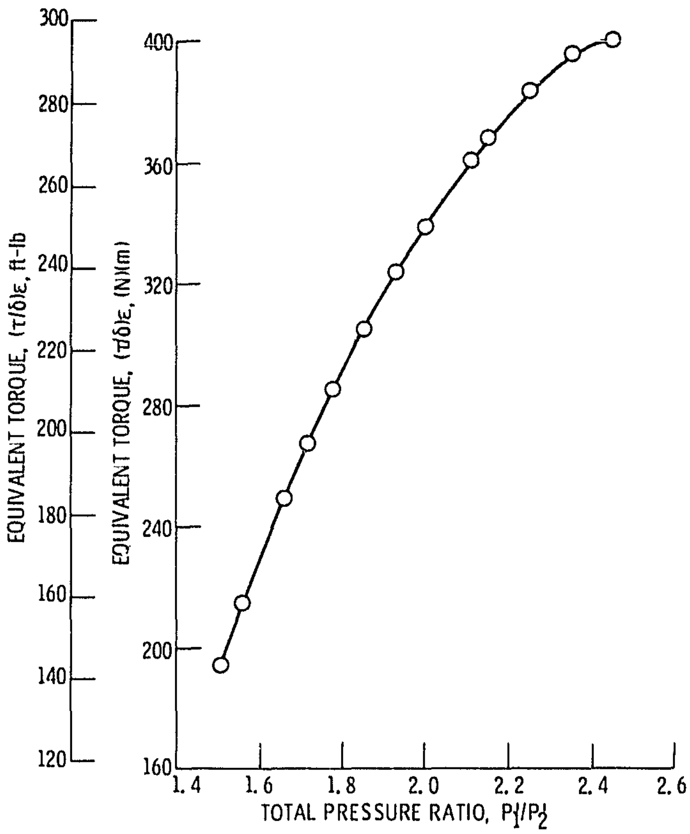

Figure 14. - Variation of torque with pressure ratio at design speed.

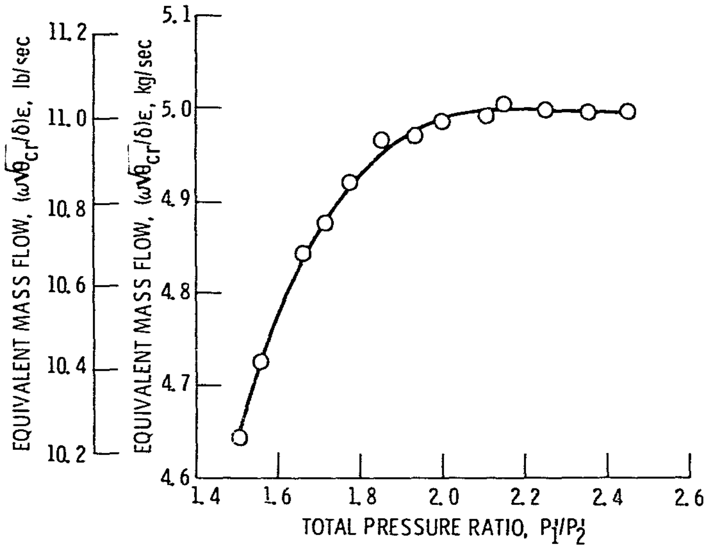

Figure 15. - Variation of mass flow with pressure ratio at design speed.

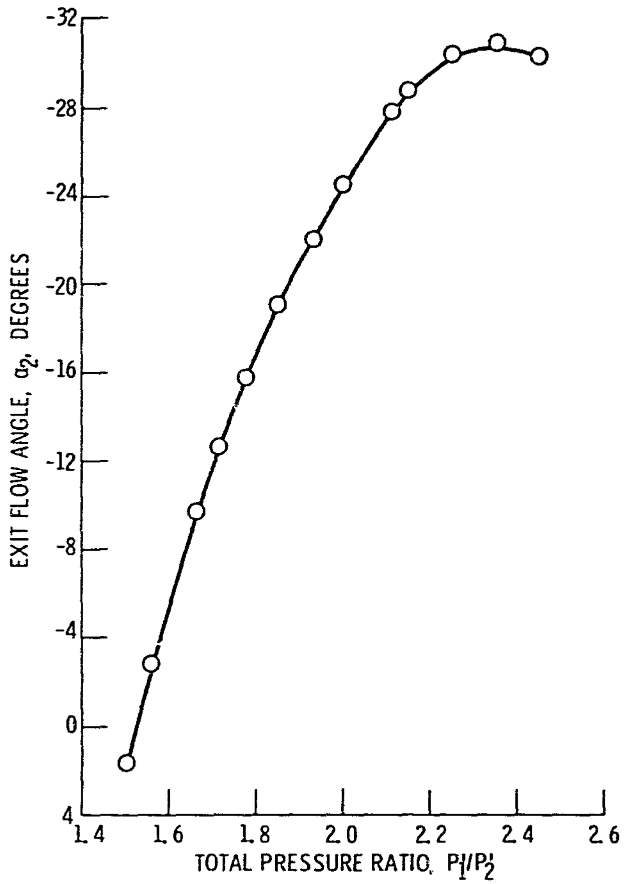

Figure 16. - Variation of exit flow angle with pressure ratio at design speed.